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The feasibility of utilising compressed natural gas as part of a systematic approach to establishing the necessary groundwork for the hydrogen based transport economy

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Abstract

One key objective for vehicle manufacturers is to develop technology and infrastructure to facilitate the progression from combustion to conversion by the year 2050. In the short to medium term however, the combustion of fossil fuels such as petrol and diesel, coupled with advanced transmission innovations and emission control technology that are governed by strict Euro VI regulations appears to be the main path forward for the transport sector and the environment.

This paper presents the feasibility of utilising the developing compressed natural gas network capabilities as part of a systematic approach to establishing the necessary groundwork for a hydrogen based transport economy. Results of tests conducted by Dublin Institute of Technology to evaluate natural gas engine performance and exhaust emissions compared with conventional fossil fuelled engines were examined. The paper also outlines Gas Networks Ireland's vision for the future of transport and the use of compressed natural gas as a fuel alternative for the transport sector.

The barriers to implementing a strategic plan for gas fuel for the transport sector are also reviewed. This includes the public's perception of gas as a transport fuel, on-board storage of gas, related weight and extreme pressure issues, range limitations, dual fuel operation, gas quality and the necessary fuelling infrastructure. By resolving some of these problems, the transition to a hydrogen based economy for transportation purposes may prove feasible by 2050.

Keywords:

Compressed natural gas, hydrogen, combustion, conversion, emissions, Hydrogen economy, Carbon economy, compression ignition, spark ignition

1.0 Introduction

This is a discussion paper from a theoretical perspective and does not express Gas Network Ireland's (GNI) policy in this area. The authors support the introduction of gas fuelled vehicles into the Irish fleet to curb pollution and promote transition to a gas economy. The paper also explores a possible pathway to developing the required filling station network suitable for future hydrogen gas fuel cell vehicles based on the current natural gas network. The DCENR White paper identifies GNI as an industry leader in the development of gas technology and infrastructure in Ireland [1].

A technology road map as shown in Figure 1 developed in 2010 by the New Automotive Innovation and Growth Team (NAIGT) formed in the United Kingdom in 2008 [2] illustrates the vehicle engineering pathway from 2000 up to the year 2050.

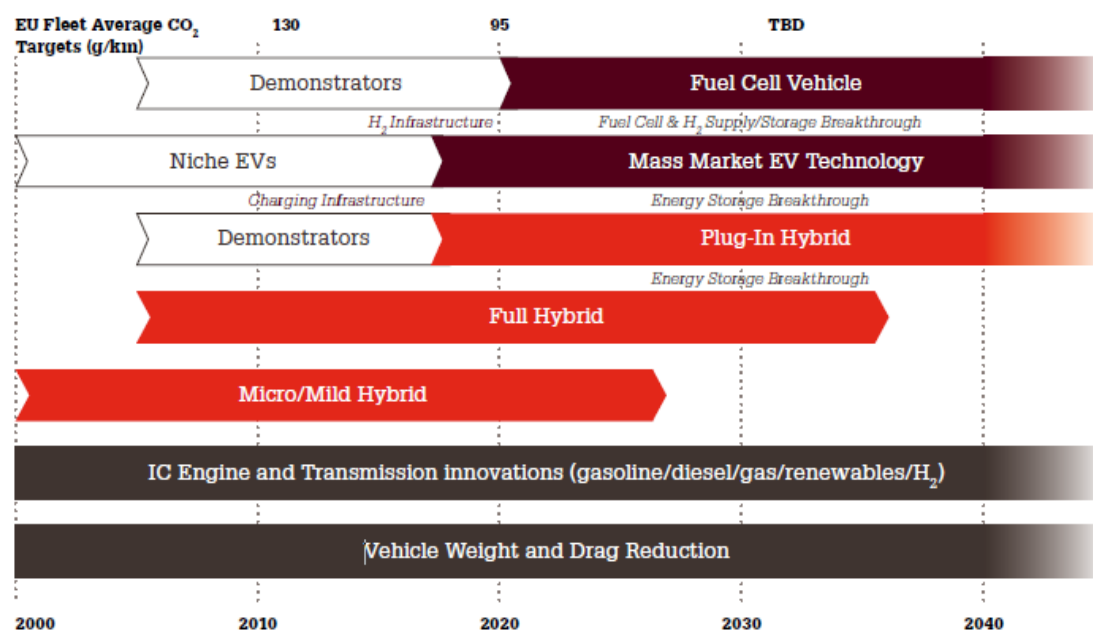


Figure 1: Technology Road Map (Source: Automotive Council UK, NAIGT)

R. Folkson 2014 [3] outlined the importance of such roadmaps for assisting in identifying major areas of technological development. The map details the various advanced technologies, alternative fuels and renewable energy options coupled with the suggested reduction in carbon dioxide (CO₂) emissions available to vehicle manufacturers and the milestone dates that correspond with their implementation. It highlights that vehicle body design and weight reduction will always offer savings on fuel consumption and CO₂ emissions. Another important element to consider is the current practice over the medium to long term of the internal combustion engine and the combustion of fossil fuels and hydrogen. Up to the year 2020 the majority of emerging technologies such as hybrid, electric and fuel cell vehicles only register as niche and demonstrator type vehicles. Research continues to be conducted into developing suitable infrastructure, gas tank connection technology and on-board storage to facilitate an acceptable mileage range similar to that experienced by present day vehicles.

1.1 Rational

Although Figure 1 highlights the contribution that electric vehicle technology may offer to fleet managers, this paper studies the benefits of promoting the use of Natural Gas Vehicles (NGV's) as part of the passenger and heavy commercial transport fleet. From 2020, fuel cell technology utilising hydrogen gas has the potential to drive the transport sector forward [2]. This paper suggests that similar to EirGrid developing the future Irish potential of electric vehicle infrastructure and technology [1], Gas Networks Ireland is strategically positioned to pursue taking the hydrogen economy forward as it possesses the necessary capabilities, knowledge and skills coupled with the gas transmission and distribution infrastructure. Further research could establish the modifications required to existing and future filling station technology and pipe network system to accommodate hydrogen gas transmission and the establishment of a filling station network. This will require additional support at government and European level in an effort to realise and develop the transition from a carbon to hydrogen based economy.

1.2 Problems facing the Carbon Economy

The internal combustion engine currently serves the transport sector worldwide. However the consequences of the combustion process regardless of the restriction being imposed on vehicle manufacturers and operators by the various Euro regulations from I to VI are now based on the growing volume of vehicles on the roads globally impacting on the planet. This has highlighted the need for radical change in how people and goods are transported for the future. Converting energy as opposed to combustion offers a realistic solution, with hydrogen gas being converted as part of an electrochemical reaction into electrical energy. This can be achieved as part of a fuel cell process, emerging as a preferred fuel and technological arrangement. Hydrogen is viewed as a clean energy that can be manufactured safely and if electrolysis using renewable energies such as solar, wind, geothermal and wave are used as part of the process it can be classified as zero emission or pollution free in a transport context from well to wheel. As oil supply heads towards peak, the price at the pumps of conventional fuels will increase due to the increase extraction and refining costs. In an effort to locate new fields as Alexander Rojey 2009 [4] suggests, oil companies' are searching regions further from the main consumer areas and drilling deeper to locate and extract crude oil and this will inevitably impact on the environment and cost of a barrel of oil. This has implications for industrialised economies such as the United States, China, Japan and Europe. The security of supply is also a major issue as the Middle East and Africa are experiencing unprecedented levels of conflict across borders. Global warming and the production of Greenhouse gases (GHG) such as Oxides of Nitrogen (NO_x), Sulphur Dioxide (SO_x) and especially Carbon Dioxide (CO₂) are causing major concern to governments worldwide. Implementing a well resourced plan to encourage the use of CNG vehicles across Europe to ease the transition to a gas economy for the motoring public and transport sector would have the result of reducing emission levels considerably and lay the groundwork for introducing a future hydrogen based transport economy.

1.3 Environmental Impact

The combustion of hydrocarbon fossil fuels by a vehicle produces harmful exhaust gas contaminants that enter the environment. Petrol engines are referred to as spark ignition engines as they use a spark plug to initiate combustion [5]. Diesel engines are compression ignition engines utilises the ignitability of the fuel at high pressure to induce auto ignition in the fuel [5]. The exhaust gas emissions for carbon based fuels, as listed in 1.3.1 are dependent on the composition of the fuel and the conditions under which it reacts with oxygen.

1.3.1 By-products of Petrol/Diesel Combustion:

- Carbon Monoxide (CO)
- Carbon Dioxide (CO₂)
- Hydrocarbons (HC)
- Oxides of Nitrogen (NO_x)
- Particulate matter (Soot)
- Sulphur (S)

The diesel engine is the current stalwart of the transport sector but it is a major polluter especially in urban areas. Diesel engines operate with excess air, producing less carbon monoxide (CO) and hydrocarbon (HC) emissions than petrol engines, but because they operate at high combustion temperatures they do produce more nitrogen oxides (NO_x) that react with other volatile organic compounds (VOC) in sunlight to form low level smog. This is damaging to the environment but also has an adverse effect on human health [4]. Although the emissions from a petrol engine are similar, exhaust by-products from the spark ignition process can be oxidised and reduced more effectively than the by-products emitted from the combustion of diesel fuel. Compression-ignition combustion has major damaging effects on air quality due to the formation in the exhaust gas stream of soot particulate matter in varying sizes. Particulates with diameters ranging from 10µm (PM₁₀) to 0.01 µm and containing carcinogenic compounds can enter the atmosphere with particulates of less than 2.5 (PM_{2.5}) being considered the most dangerous [4].

The majority of the diesel fuel sold in Europe is classified as ultra low sulphur diesel (ULSD). This depends on where the crude originates from. Sulphur dioxide (SO₂) in the emissions can lead to the formation of sulphuric acid in the atmosphere, producing acid rain, damaging forests, buildings, structures, wildlife, fish stocks and polluting fresh water supplies [4]. To control these emissions, extra processes and units are incorporated into the exhaust control system. Select catalytic reduction (SCR)

include units such as a soot filter coupled with a Urea dosing process administered through the fuel injection system used for soot filter regeneration, catalytic converter and a DeNox unit for storing and reducing NO_x. Alternatively an ammonia solution such as AdBlue can be used to reduce NO_x emissions in the exhaust gas stream. This process is governed by strict Euro VI regulations which include controlling the levels of ammonia that can be emitted from the tail pipe.

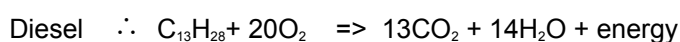
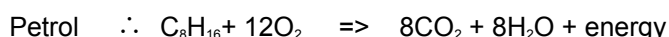
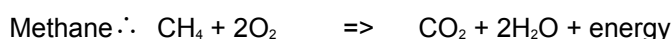
The damage inflicted on the environment by the continued use of diesel fuel is a compelling argument for advocating a change to compressed natural gas as an alternative to diesel fuel. As part of the transition to using compressed natural gas vehicles this paper suggests that petrol as opposed to diesel can be used to extend the range of compressed natural gas vehicles based on the tests conducted on a Bi-Fuel vehicle at Dublin Institute of Technology. The results of this are outlined later in this paper.

1.4 Utilising Compressed Natural gas and Hydrogen

With reference to the generation of electricity, Vincent Lagendijk and Geert Verbong 2012 [6] outline the carbon based fuel energy transition process through history from wood to coal, coal to oil and from oil to natural gas. A natural progression suggests that the future transport fuel being hydrogen. This is based on the fact that if one examines the composition of each of the fuels such as wood, coal, oil etc., the percentage of carbon reduces and the percentage of hydrogen, the main energy carrier increases. Therefore during combustion hydrogen provides the energy requirement. The residue that remains after the process is carbon and this has manifested itself into by-products of pollution that will always be present as long as combustion is used to power the transport sector.

Compressed natural gas is mainly Methane (CH₄) which is a greenhouse gas. Whereas conventional fuels such as diesel and petrol are a complex blend of various compounds to ensure ideal combustion and reduced emissions. In their simplest form as outlined in Example 1 if representative formula for methane (CH₄) with a H/C ratio of 4:1, light diesel (C₁₃H₂₈) with a H/C ratio 2.2:1 and petrol (C₈H₁₆) with a H/C ratio of 2:1 are compared under ideal combustion conditions. It is evident that the consequence of reduced energy/power for natural gas (Methane) is compensated by the reduction in the presence of carbon dioxide and water vapour another greenhouse emission.

Example 1: Ideal combustion results in carbon dioxide, water vapour plus energy [7]



This example shows the high level of CO₂ that can be emitted from conventional hydrocarbon fuels under ideal combustion conditions. It also highlights that compressed natural gas may suffice [8] as a medium term transitional measure until hydrogen technology is mature and becomes more mainstream as a transport option, generating major reductions in CO₂ emissions. It is worth noting however that hydrocarbon fuels and hydrogen gas used in high temperature combustion have the potential to produce oxides of nitrogen (NO_x) which is more hazardous to humans and the environment than CO₂ [5].

Human perception plays a major role in gaining acceptance of a new product or technology. Gas, and in particular hydrogen is associated with explosions such as the hydrogen bomb and the Hindenburg Airship disaster. The bench mark that is constantly used in an Irish context is the attempted introduction of Liquid Petroleum Gas (LPG) in the 1980's. The major problem with this concept was its retrofit nature that required considerable modification of the engine and on-board storage that generally occupied the boots storage capacity to house the gas cylinder. Unlike CNG and H₂, LPG is mostly butane or propane based and is heavier than air which means it had the capacity to lodge in confined spaces presenting a potential for build-up and possible detonation. This formulated bad press at the time surrounding the use of LPG as an alternative fuel option although it was and is used successfully worldwide for powering passenger vehicles.

Table 1 presents a fire risk comparison of three fuels; hydrogen, petrol vapour and natural gas. The table highlights some interesting points that contradict general perceptions regarding the safe use of

CNG and H₂. On the positive side the lower density values of CNG and H₂ in comparison to petrol suggests that in a leak scenario the gas based on its buoyancy would quickly disperse and its high diffusion coefficient value confirms that H₂ and CNG would rapidly dissipate in air making it less of a fire hazard [9].

Table 1: Fire risk comparison of three fuels [7]

Property	Hydrogen	Petrol Vapour	Natural Gas
Density kg/m ³ (at normal temp/pressure)	0.084	4.40	0.65
Diffusion Coefficient in air (cm ² /s)	0.610	0.05	0.16
Specific Heat at Constant Pressure (J/Gk)	14.89	1.20	2.22
Ignition Limits in air (vol. %)	4.0-75	1.0-7.6	5.3-15
Ignition Energy in air (mJ)	0.02	0.24	0.29
Ignition Temperature (°C)	585	228-471	540
Explosion Limits (in air)	18.3-59%	1.1-3.3%	5.7-14%
Flame Temperature in air (°C)	2045	2197	1875

For density and diffusion in air of natural gas compared with hydrogen gas, if the concept put forward by this paper was developed, the sealing integrity of the current pipe network may need to be evaluated to insure hydrogen could not escape from its current or future supply pipe network. In other areas such as specific heat, ignition temperature, and explosion energy, hydrogen and natural gas are ranked as safe fuels but with regards to ignition limits, energy and flame temperature, they are ranked as less safe than petrol [9]. As outlined by the California Energy Commission [10] hydrogen hazards are usually managed easier than hydrocarbon fuels because Hydrogen is lighter than air and it disperses as it burns upwards. Hydrogen can cause brittleness in some materials, including metals and can generate electrostatic charges and sparks through flow or agitation. Compressed natural gas however is considered non-corrosive [11].

1.5 Types of Natural Gas Vehicles

To facilitate a perceived lack of infrastructure and range anxiety for customers which is a main barrier to commercialization, natural gas vehicles come in three types;

- Dedicated engine technology using 100% natural gas
- Duel fuel; operates on natural gas but using diesel injection for ignition and as a reserve fuel.
- Bi-Fuel; operates on natural gas while retaining the ability to use petrol as a reserve fuel.

Globally there are approximately 15.2 million natural gas vehicles on the roads, ranging from cars, vans, delivery trucks, buses and heavy trucks, mainly in urban areas [12].

The Diesel engine (compression ignition) based on its high compression ratio (15-20:1) and robust design is more suited to heavy road haulage commercial vehicle conditions. But natural gas is more compatible with a compression ratio (10-12:1) of a petrol engine. The compression ratio for a Bi-Fuel engine would be typically 13.5:1, based on the extremely high antiknock quality of natural gas (RON120). The modifications to a diesel engine would include the fitting of spark plugs, inserts, piston design, hardening of valve seats, upgraded thermal management components such as oil coolers, larger radiator, heat shields, exhaust components and also modification of the engine management system to facilitate control of component, responses times and exhaust emissions [13].

The petrol engine as part of the Bi-Fuel arrangement, requires less modification as both arrangements for equipment configurations; operating principles and emissions are similar. The output of the natural-gas engine is approx. 10 – 15% lower than that of the petrol engine due to the lower fuel mass necessary for stoichiometric combustion ratio (17.2:1) as well as a lower volumetric efficiency due to

the injected natural gas. Higher compression can boost performance while simultaneously increasing efficiency [5].

Natural gas can be stored on-board a vehicle in a steel, aluminium or composite tank at approx. 200 – 250bar. When the ignition is switched on; gas under pressure flows to a high pressure regulator where it is reduced in pressure to approx. 12bar. From here the gas flows to a two stage low pressure regulator where its pressure is further reduced to 0.5bar in the first stage and 4.5 – 7 inches of water in the second stage before being delivered to a gas mass sensor/ mixture control valve which is responsible for the air/fuel mixture. The CNG distributor adaptor then delivers the gas to the engine combustion chamber as part of a low pressure common rail injection system [14]. As part of this study, a Bi-fuel vehicle was tested at Dublin Institute of Technology and its operation in petrol and compressed natural gas modes were compared and evaluated. This testing and analysis is covered in a later section of this paper.

At ambient temperature and pressure, gaseous fuels are much less energy dense than liquid fuels. As a result, vehicles running on gas can require a significantly larger volume of fuel to travel a comparable distance (range anxiety) and this can result in increased vehicle weight [12]. On-board storage of natural gas in most instances is similar to hydrogen. Both gases can be stored on-board at a pressure of 200bar. To reduce the tank weight and increase volume, research is being conducted for hydrogen gas to be stored at 700bar. To further reduce tank size and weight, gas can be liquefied or cryogenically stored at temperatures of -160°C for CNG (liquefied natural gas (LNG)) and -253°C for H₂. Hydrogen gas can also be stored in metal hydrides which are a combination of metallic alloys that act like a sponge to absorb H₂ under moderate pressure and then release it when heated [15].

1.6 Conversion as opposed to Combustion

Hydrogen can be used in two ways to power a vehicle. Hydrogen as previously documented in the energy road map utilising fuel cell technology can also provide electrical power to drive a road vehicle. The roadmap (Figure 1) shows that the automotive industry has been researching fuel cell technology and introduced demonstrators into the market worldwide in an effort to achieve commercialisation by 2020 and full implementation by 2050. One of the main barriers to the changeover to a hydrogen economy is the establishment of an adequate hydrogen infrastructure to move this project forward past 2020.

At a Natural Gas Vehicles Conference held at Croke Park, Dublin in 2011, Manual Lage, the then General Manager, Natural Gas Vehicles Europe spoke about the use in vehicles of a methane/hydrogen mixture that offered a number of advantages as a bridge solution for a future hydrogen fuelled transport:

- This mixture can be used in existing NGV engines and vehicles with minor engine resetting
- The on-board fuel storage uses the same type of tanks and fittings with some specification changes in materials
- The H₂ content considered (up to 30%) does not alter the autonomy of the vehicles
- There is an immediate impact on CO₂ emissions
- The use of compressed H₂ on a large basis will push ahead the development of hydrogen production and logistics.

The example given at the time of an in-service vehicle running on a methane/hydrogen mixture was a bus operating in the Dunkirk, France since July 2009 [16]. This is a prime example in a European context of how the use of natural gas and hydrogen complement each other and paves the way for an eventual hydrogen economy.

Open discussion on the concept of acclimatising customers and fleet operators in Ireland to using gas as a transport fuel by removing their fear and perception of gas as a dangerous fuel needs to be advanced. A step approach can be achieved by preparing the way forward with a current gas product such as compressed natural gas. As part of a long term strategy, filling station networks and infrastructure under development could be designed to facilitate hydrogen use.

1.6.1 Fuel Cells

A fuel cell is an electrochemical device that directly converts the chemical energy of a fuel (hydrogen) and an oxidant (oxygen) into low voltage d. c. electrical energy [17]. The bi-products of this process are heat and water. If the process of producing hydrogen is achieved using renewable energy and no combustion or on-board reforming of a hydrocarbon fuel is used, then the process of well to wheel should result in zero emissions. The electricity generated by a fuel cell stack is used to drive on-vehicle motors to drive the road wheels and provide ancillary power for the vehicle systems. A regenerative process is also used to reclaim energy from the braking process of the vehicle. Although vehicle technology for combustion and conversion differ significantly, the designs for on-board storage, dispensing equipment, the filling station network and gas transport infrastructure for compressed natural gas and hydrogen are relatively similar. Both require more research and development.

1.7 Case Study

Gas Networks Ireland owns, operates, develops and maintains the natural gas transmission and distribution infrastructure network in Ireland. Gas Networks Ireland operates a world-class modern gas network through the flow of gas from entry points with Scotland and the Corrib entry point in Mayo. The current gas network in Ireland is made up of over 13,685km of pipeline, including 2,467km of transmission network, 11,218km of distribution network, and 398km of subsea interconnectors. Gas Networks Ireland serves almost 674,000 gas customers in the power generation, industry, SME, and domestic sectors. This includes over 642,836 homes and 25,232 businesses connected to the gas network in over 160 population centres, and throughout 19 counties. Gas Networks Ireland's focus is on continued growth and expansion while reducing carbon footprint and maintaining the highest standards of safety and reliability.

In a transport context Ireland is facing an emissions crisis in transport which requires immediate action. Ireland has a binding obligation that 10% of all transport energy must come from renewable sources by 2020. Air quality is also an area of major concern for the World Health Organisation (WHO) with the particulate matter emissions from diesel of high concern. Presently all road fuels are imported into Ireland and 98% are oil based. Since 1st January 2016 gas supply in Ireland has changed dramatically with up to 60% of gas demand being met with an indigenous supply from the Corrib gas field. With the introduction of renewable gas, Ireland has the opportunity to achieve energy independence in relation to gas while maintaining system security with a connection to the larger European gas network. If CNG is supported and developed, the Irish transport sector would have access to an indigenous fuel source for the first time, resulting in energy diversity and helping to address concerns about security of fuel supply for the transport sector. At a European level the requirement to reduce our dependence on diesel has become of paramount importance and this is reflected in the publication in October 2014 of the European Alternative Fuels Directive. This European directive aims to promote the use of alternative fuels in transport. It places obligations on each member state to develop the necessary infrastructure to support alternative fuels adoption. The targets set by the directive also requires each member state to publish a National Policy Framework by the end of 2016 which will set out an appropriate number of stations, required by 2025 in order to accommodate vehicle range and travel routes.

1.8 Future Vision

In order to provide full national coverage, GNI is proposing to develop a 70 – station CNG fuelling network, co-located in existing forecourts, on major routes or close to urban centres to satisfy the requirements of the Alternative Fuels Directive and to provide a comprehensive refuelling station network. This would allow a transition to both natural gas and renewable gas as an alternative fuel. The existing natural gas network can be utilised to facilitate the installation of the required number of CNG refuelling stations and act as a national vehicle refuelling network, giving the commercial transport sector access to a cleaner, cheaper fuel that mirrors the operational performance of diesel. Figure 2 provides an overview of the proposed locations of public CNG refuelling stations to be located along core road networks and gas network intersection points. In 2016 Gas Networks Ireland will deliver the first two publicly accessible CNG stations located in the Dublin and Cork regions.

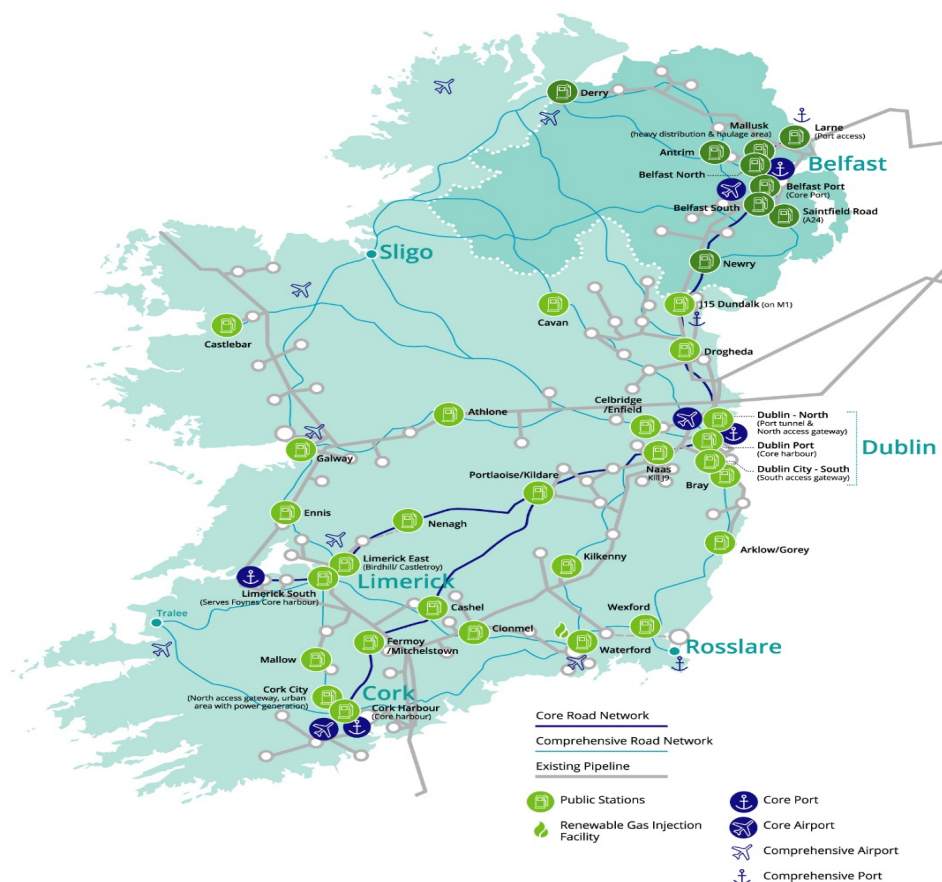


Figure 2: Proposed locations of public CNG refuelling stations (Source: GNI)

1.9 Testing of a Bi-Fuel Vehicle

As part of this research, testing of a 3500kg, 1.8 litres Mercedes Sprinter bi-fuel vehicle (CNG/Petrol) was conducted in the Advanced Vehicle Test Laboratory in Dublin Institute of Technology (DIT). The test results allow for an evaluation to be made of the vehicle driving in gas and petrol modes. The equipment used to test the power and torque outputs in petrol and natural gas modes at standard air temperature and pressure was a MAHA Rolling Road Dynamometer and the maximum results for each mode are outlined in Table 2. When conducting the tests, the general observation was that the vehicle performed better when driven on the rolling road in gas mode.

Table 2: Max. Power and Torque outputs at Standard Air Temperature and Pressure

Petrol Mode	Max. Engine Power	Max Torque
Oil Temp: 85-92°C	121.8 kW at 5475 rpm	237.5 Nm at 3550 rpm
Gas Mode	Max. Engine Power	Max Torque
Oil Temp: 85-92°C	122.7 kW at 5415 rpm	226.9 Nm at 4020 rpm

This is borne out by the relatively similar results obtained for power and torque in each mode. In gas mode, more power (0.9kW) was generated at a lower speed (60 rpm lower) than in petrol mode but this is offset by the increased torque achieved by the vehicle in petrol mode (10.6Nm) at a lower speed of 3550 rpm (470 rpm lower).

A BrainBee 4 gas analyser (AGS-200) was used to conduct static exhaust gas tests on the Mercedes Sprinter. The vehicle was fitted with a catalytic converter to oxidise and reduce exhaust emissions. The supervised tests process was similar for each mode with the vehicle warmed up to normal operating temperature and the rpm increased in increments of 500rpm and held for 30 seconds to obtain a steady state reading. The results for each mode are listed in Tables 3 and 4.

Table 3: Petrol Mode Emission (Oil Temp: 80-98°C)

Speed rpm	Lambda (λ)	CO %Vol	CO ₂ %Vol	HC ppmVol	O ₂ %Vol
Idle (700-800)	1.006	0.01	15.5	0	0.14
1500	1.003	0.01	15.5	0	0.08
2000	1.003	0.01	15.5	0	0.08
2500	1.002	0.01	15.5	0	0.07
3000	1.002	0.01	15.5	0	0.07
3500	1.006	0.01	15.3	0	0.14
4000	1.004	0.01	15.4	0	0.10

Table 4: Gas (Methane) Mode Emission (Oil Temp: 80-98°C)

Speed rpm	Lambda (λ)	CO %Vol	CO ₂ %Vol	HC ppmVol	O ₂ %Vol
Idle (700-800)	1.008	0.01	12.0	102	0.33
1500	1.002	0.01	12.2	37	0.11
2000	1.002	0.01	12.2	15	0.08
2500	1.004	0.00	12.0	54	0.18
3000	1.002	0.00	12.0	32	0.09
3500	1.003	0.00	12.0	6	0.08
4000	1.004	0.00	12.0	1	0.10

Observation of the results show similarity in areas such as the lambda reading which are based on the stoichiometric value (14.7:1) associated with spark ignition combustion. The CO levels are very low (0.00-0.01) especially for gas mode. CO₂ levels for petrol mode are lean and reflective of the lambda reading and a CO₂ reading of 12.0 for gas could suggest an air/fuel ratio of 17.2:1 (ideal for Methane) or 13.5 approx., a slightly richer mixture. The presence of HC emissions in the gas stream of the gas mode suggests that there may be a problem with the oxidation process of the converter and this is reflected in the low O₂ reading across the testing process. This suggests that there is insufficient oxygen to satisfy the oxidation process of the converter. The National Car Test (NCT) states in its criteria that a HC test is not required for passenger vehicles operating on CNG.

An observation of the test results may conclude that the converter is developing a fault or the vehicle emission control is set-up for petrol application. This would support the case to introduce dedicated Natural Gas Vehicles onto the market to eliminate any problems that may be associated with dual/bi-vehicle use.

1.10 Conclusions and Future Research

The damaging impact of the continued combustion of hydrocarbon fuels is becoming more and more evident with increased greenhouse gas levels, especially CO₂ resulting in global warming. Moving away from a low carbon economy by 2050 involving some form of limited combustion as outlined in the White Paper [1] and progressing to a hydrogen economy utilising conversion in the form of fuel cell technology as proposed by this paper has merit. Views and opinions on this topic are very strong and

having consulted with various stakeholders who hold different opinions, there is an acceptance that more research needs to be conducted into the transition to a hydrogen economy. Timing is critical and more direction at EU/Global level needs to be applied to establishing a definitive pathway forward. The incentivised encouragement by the government/EU and use of gas in a transport context will require a behavioural shift on behalf of the public and this will require a process of education and acclimatisation to eliminate the public perception and fear of gas as a dangerous fuel. If the concept of utilising the existing pipe network to accommodate hydrogen transmission were to be pursued then future research is required to establish the requirements of such an arrangement. Research would also need to be conducted into the compatibility of various components, materials and structures that form part of a system.

1.10.1 Limitations of Research

Limitations of this research centred on disseminating the vast amount of information available on this topic and the varying opinions of different sections of industry and academia. There was also an issue regarding the securing of a Dual-fuelled Mercedes Sprinter (CNG/Diesel) and a diesel Sprinter for evaluation and comparison purposes. The availability of an Oxides of Nitrogen (NO_x) tester would have contributed considerably to the evaluation results obtained while testing the bi-fuel vehicle. But it is envisaged that these will form part of future research being conducted in the Transport Engineering section at DIT.

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